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ACCURACY OF THE RTCC "LM DESCENT PERCENT MARGIN" DISPLAYS FOR THE LUNAR LANDING MISSION

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Landing Analysis Branch

MISSION PLANNING AND ANALYSIS DIVISION

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PROJECT APOLLO

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By Gregory L. Shaffer and Edwin G. Dupnick
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ACCURACY OF THE RTCC "LM DESCENT PERCENT MARGIN" DISPLAYS FOR THE LUNAR LANDING MISSION

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SUMMARY

A study was conducted to determine the accuracy of the Real-Time Computer Complex (RTCC) displays of predicted fuel and oxidizer margin predicted for touchdown during the powered-descent braking phase and the predicted propellant margin during the approach phase, collectively known as the LM Descent Percent Margin (LM DES) displays. The results of ten selected powered-descent simulations indicated that the LM DES displays are relatively accurate except for several extreme test cases.

The logic for the fuel and oxidizer margin display is insensitive to thrust deviations, and the accuracy of the propellant margin display is degraded by navigation errors.

INTRODUCTION

This document is written in response to reference 1, which requested a study to determine the accuracy of the RTCC LM DES displays and hover time calculations as formulated in reference 2. There are two LM DES displays, each with distinct modes of computation and scaling. The ten-minute display used during the powered-descent braking phase presents the predicted percent of usable descent propulsion subsystem (DPS) fuel and oxidizer that will remain at lunar touchdown (defined as margin) as a function of burn time or phase elapsed time. Nominally, 7 percent remains. A usable quantity is that actually available for expenditure and should be distinguished from a loaded quantity, from which that trapped in lines, etc., must be subtracted in order to determine usable. The 200-second display is used during the approach phase and presents the predicted percent of usable DPS propellant that will remain at lunar touchdown as a function of burn time. The margin indicates the safety of the crew and trajectory, which is a prime concern of the descent monitoring activity. Hover time is a conversion of the margin into a parameter which is perhaps more meaningful to the LM crew.

The study utilized ten selected powered-descent simulations (table I) for an analysis of the inaccuracies involved in these displays.

BRAKING PHASE DISPLAY

The ordinate of the braking phase, or ten-minute, display is the predicted usable fuel and oxidizer margin at LM touchdown in percent of total usable DPS fuel and oxidizer; the range is from +7 percent to -4 percent. The abcissa is time from DPS ignition; the range is zero to ten minutes. The fuel and oxidizer margins are calculated according to equations in the appendix.

Reference 2 requested that a polynomial be used to compute required propellant with the navigated horizontal velocity as the independent variable. To obtain the coefficients of this polynomial, or curve fit, the percent of usable propellant remaining instantaneous minus the actual propellant remaining at touchdown was plotted against navigated horizontal velocity for the ten test cases. The collinearity of the resulting data precipitated a decision to use the nominal (case 1) as fairly representative. Case 1 and the polynomial are presented in figure 1. Using this polynomial, the fuel and oxidizer margins were predicted and are shown in figure 2. The fuel and oxidizer margin calculations were so close that the curve in figure 2 adequately represents either quantity. (Normally in real time, the fuel margin locus will be depicted by small "F" letters and the oxidizer margin by small "O" letters.) The serpentine effect of the curves seems to stem from the fourth-order polynomial, least-squares curve fit. Note that the display scaling suggested by reference 2 was inadequate for the margins encountered.

In figure 2, cases 8 and 10 peak up near the end. This is because the DPS engine throttles down later than nominal for a lower thrusting engine (table I). However, when the engine throttles down later, more horizontal velocity is nulled per unit of time. Thus, at a given time, the horizontal velocity will be less than usual, which results in less than usual required propellant (from the curve fit) and an increased margin. Note that a cross-range distance error has the same effect as a low thrusting engine - it also causes a late throttle down.

The percent error in the braking phase display (fuel and oxidizer margin) are shown in figure 3. Percent error is computed by subtracting the actual margin from the predicted margin, multiplying by 100 percent and dividing by the actual margin. (See table II for values of the actual margin.) Cases 8 and 10 (low thrust engines) exhibit negative percent errors because the time rate of decrease in horizontal velocity is less than nominal, thereby requiring, for a given time, more propellant and resulting in less margin than what will actually be the case. Case 9 on the other hand represents a high thrust engine. In this simulation, horizontal velocity is nulled faster than usual for a given time. Since the remaining propellant quantity is not much different than the nominal for any given time, the predicted required propellant will be lower due to a lower horizontal velocity. This leads to the conclusion that the margin will be greater than usual and results in a positive percent error.

Figure 4 presents the guaranteed hover time in seconds based on fuel and oxidizer margin as a function of time from DPS ignition. (The hover time actually appears as a number, or digital, on the LM DES displays but is plotted in figure 4 for illustrative purposes only.) Hover time is computed as a scalar multiplier of margin with the assumption that 1 percent of margin is equivalent to 18.74 seconds of hover time. Reference 2 assumes that in order to hover, the LM must have a thrust setting of 24 percent (of 10 500 lb) and, thus, will consume 1 percent of propellant in 18.74 seconds. Since the hover time is only a scalar multiplier of margin, the associated errors would be identical to those of figure 3.

APPROACH PHASE DISPLAY

The approach phase, or 200-second, display has an ordinate of predicted propellant margin in percent of usable propellant (from +7 percent to -4 percent). The abcissa is time from 0 to 200 seconds, which should correspond to the interval 480 to 680 seconds from DPS ignition. The propellant margin is calculated according to equations A-3, A-4, and A-5 of the appendix.

Reference 2 implies that the equation for ΔV_R, the estimated required ΔV from present position to touchdown, included only the low gate target acceleration vector, excluding the lunar gravity vector. The percent error resulting from this omission was quite significant and is shown in figure 5 for case 1. Discussions with Flight Control Division personnel resulted in the present form of the equation, which includes the lunar gravity vector. Reference 2 also had a negative sign preceding the jerk term with the assumption that the jerk term was negative. The negative algebraic sign is inconsistent with the derivative of ΔV_R and should be changed for the real-time computations.

The time history of the approach phase display (predicted propellant margin in percent of usable propellant), or 200-second plot, is presented in figure 6. Cases 8 and 10 represent low thrust engines and provide more propellant margin. Since the trajectory was targeted using a low thrust engine model, cases 8 and 10 demonstrate more efficient use of propellant in satisfying the guidance targets. Figure 7 presents the percent error in the approach phase plot. The errors are relatively small and approach zero except for cases 9 and 10. The significant feature of these cases is that each contain IMU errors and do not actually satisfy the low gate targets. Case 9 was lower in altitude than the nominal and used less ΔV than expected for the vertical descent phase, which resulted in a positive error in the margin prediction. Case 10, on the other hand, was higher than nominal and resulted in a negative error.

Figure 8 presents the guaranteed hover time, in seconds, based on propellant margin. Since this curve is actually a scalar multiplier of the propellant margin plot (fig. 6), the inaccuracies associated with it are identical to those of figure 6.

CONCLUSIONS

The study has shown that the fuel, oxidizer, and propellant margins predicted by the logic presented in reference 2 are relatively accurate except for a few isolated thrust deviation cases.

The logic for computing the ten-minute, or fuel or oxidizer, margin curve is insensitive to thrust deviations, particularly negative or low-thrust situations. This is because the predicted required fuel or oxidizer is computed as functions of navigated horizontal velocity, which is also insensitive to thrust deviations.

The 200-second display has smaller errors than the ten-minute display. In this case the analytic logic is perceptive to thrust deviations, but not to navigated errors. Navigated errors cause problems in that the low gate targets cannot be met, causing an unknown error in the margin calculation. Thus the assumption of requiring 120 fps to go from low gate to the lunar surface is not always valid. However, there seems no way of predicting a more realistic number in real time.

Because cases 9 and 10 are considered to be worst type combinations of errors , the inaccuracies of figure 6 would rarely be greater than those associated with cases 9 and 10. It should be noted, as pointed out in the discussion, that equation A-3 of the appendix must include the lunar gravity effect and have a positive sign associated with a positive value of jerk.

For real-time utilization of these plots, emphasis must be placed upon having explicit knowledge of engine performance and evaluating the predicted fuel and oxidizer margins accordingly. For a valid evaluation of the propellant margin, the correctness of the navigation state must be known.

TABLE I.- LANDING SIMULATION TEST RUNS[a]

Purpose	Run no.	Initial errors	IMU errors	Terrain profile	Terrain slope, deg	Thrust deviations
Nominal	1	No	No	Smooth	0	0
Initial condition errors alone	2	$+3\sigma$	No	Smooth	0	0
	3	-3σ	No	Smooth	0	0
Terrain variations alone	4	No	No	III-P-11A	0	0
	5	No	No	III-P-11A	+1	0
	6	No	No	III-P-11A	-1	0
Thrust accelerations alone	7	No	No	Smooth	0	$+3\sigma$
	8	No	No	Smooth	0	-3σ
Worst-case runs	9	-3σ	-3σ	III-P-11A	-1	$+3\sigma$
	10	$+3\sigma$	$+3\sigma$	III-P-11A	+1	-3σ

[a]These test runs were selected at MSC to check out the landing-maneuver simulations. The initial errors were determined as the worst-case errors. The 3σ IMU errors are taken as 3mr alignment, 0.02 ft/sec^2 accelerometer bias, and 450 p.p.m. accelerometer scale factor along each axis. No LR random or bias errors are included. The effects of lunar terrain altitude variations on the landing trajectory were investigated with terrain profile A for site III-P-11 as being the most difficult to land at of those currently under consideration. The $+1^\circ$ slope is a terrain high and the -1° slope is a terrain low. The 3σ thrust-acceleration deviations are +.9 percent and -2.5 percent of 10 500 lb at the start of the DPS burn. Further information may be found in references 3 and 4.

TABLE II.- ACTUAL MARGINS

[Used to calculate percent error]

Case no.	Actual propellant margin, percent	Actual oxidizer margin, percent	Actual fuel margin, percent
1	7.62	7.68	7.43
2	7.53	7.58	7.42
3	7.78	7.84	7.70
4	7.62	7.67	7.53
5	7.91	7.96	7.82
6	7.26	7.32	7.17
7	9.29	9.33	9.22
8	7.62	7.68	7.54
9	6.78	6.83	6.68
10	10.91	10.96	10.84

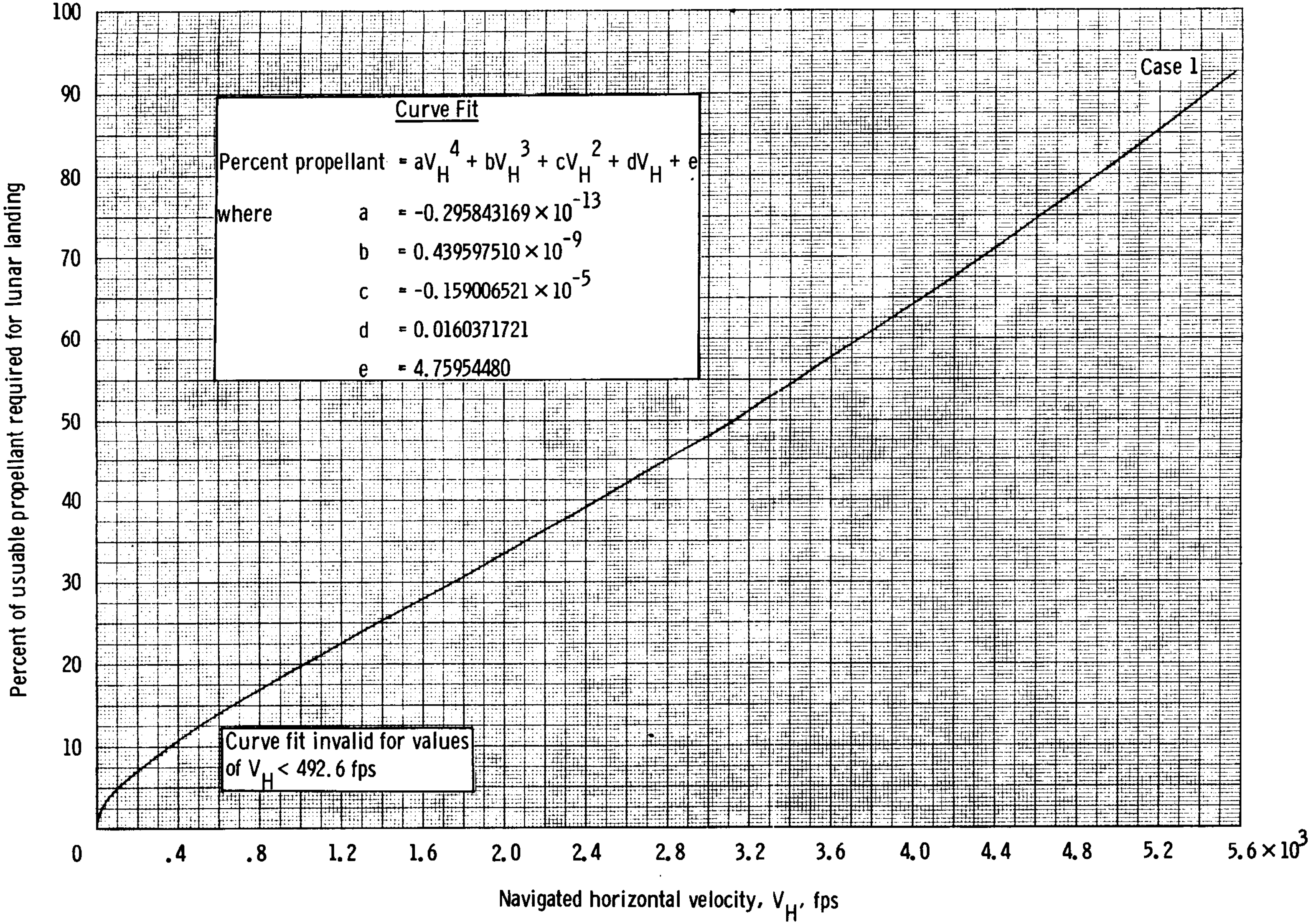

Figure 1. - Usable propellant required for lunar landing as a function of navigated horizontal velocity.

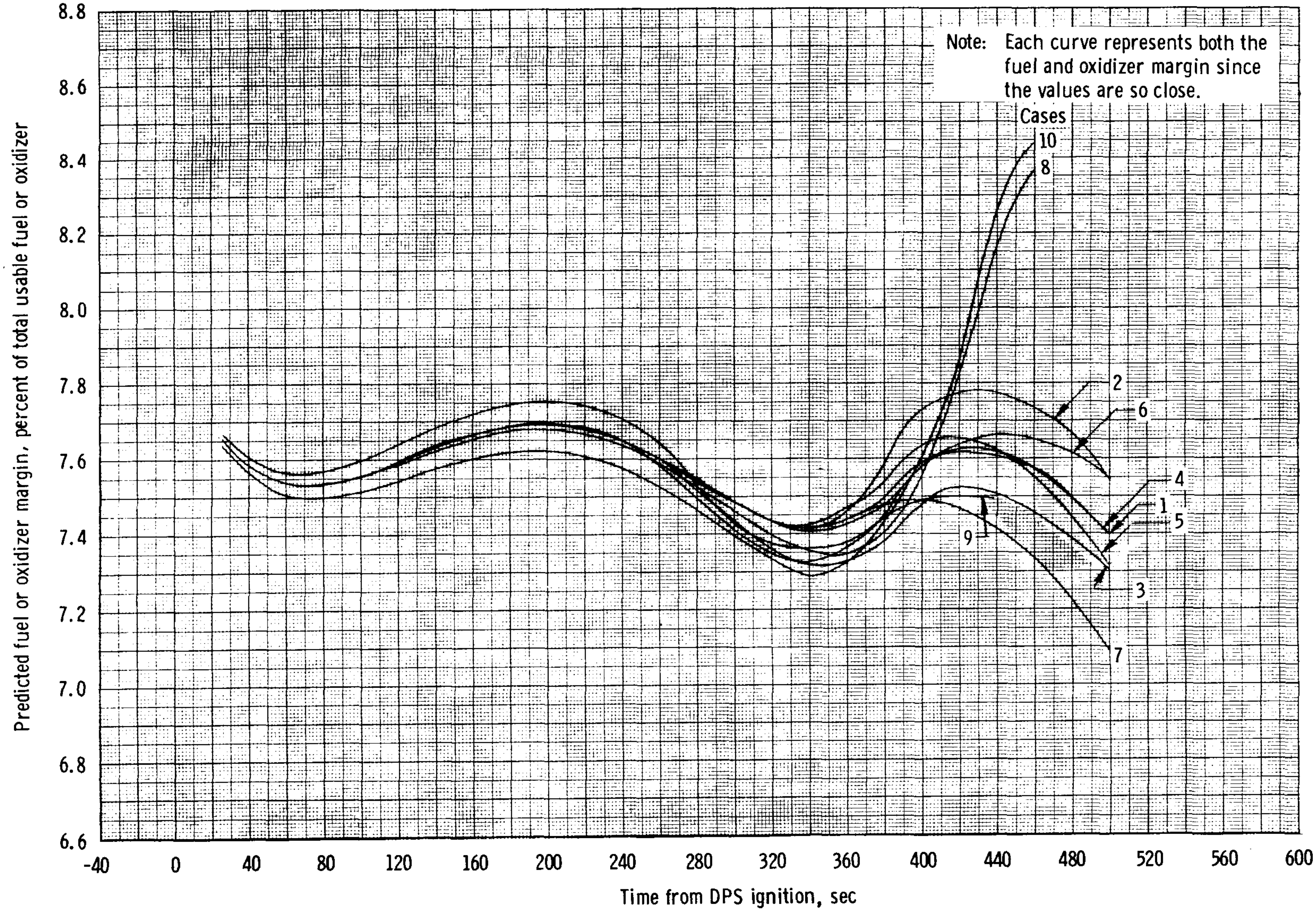

Figure 2. - Time history of the predicted fuel and oxidizer margins during the braking phase.

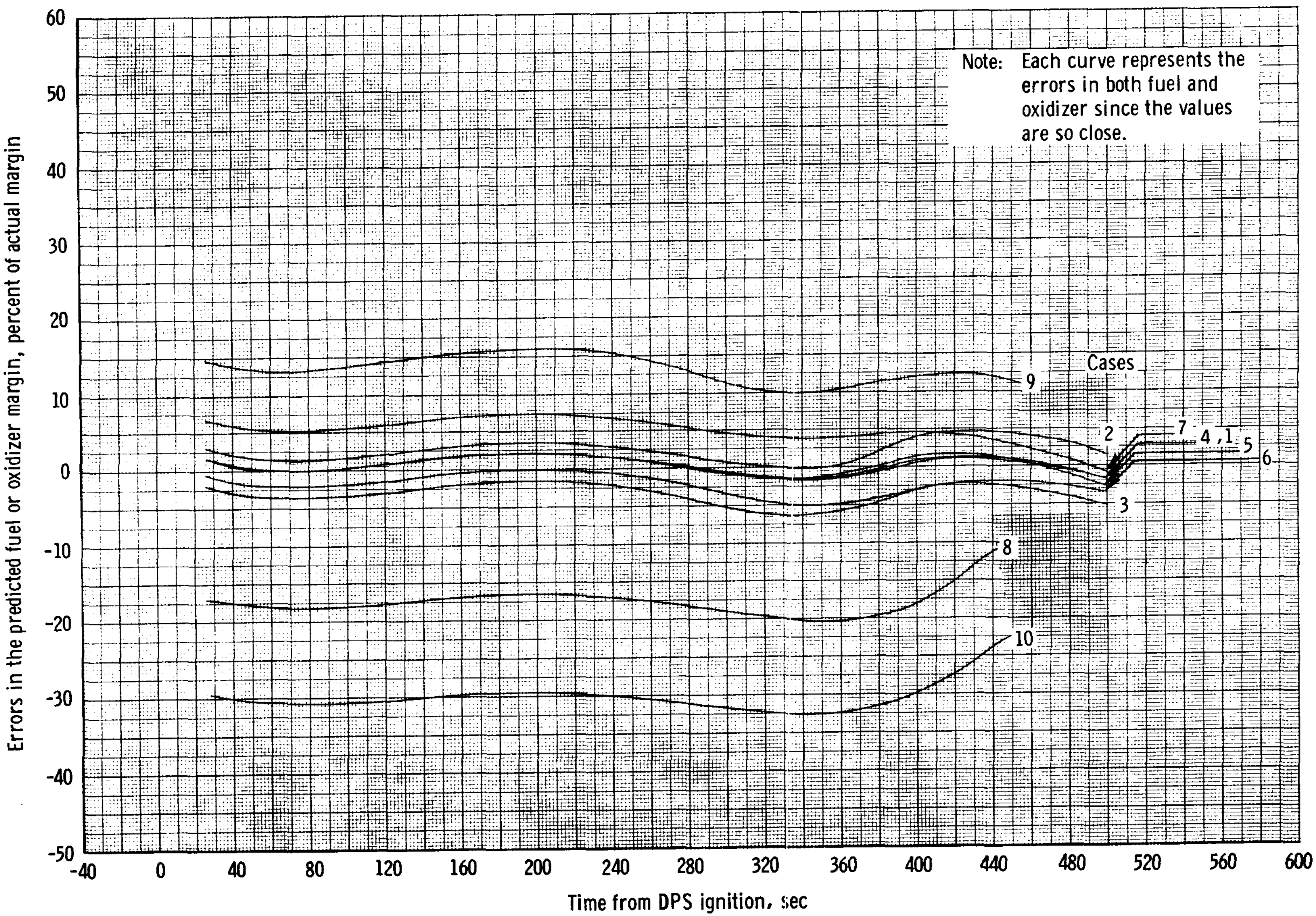

Figure 3.- Time history of the errors in the predicted fuel and oxidizer margin during the braking phase.

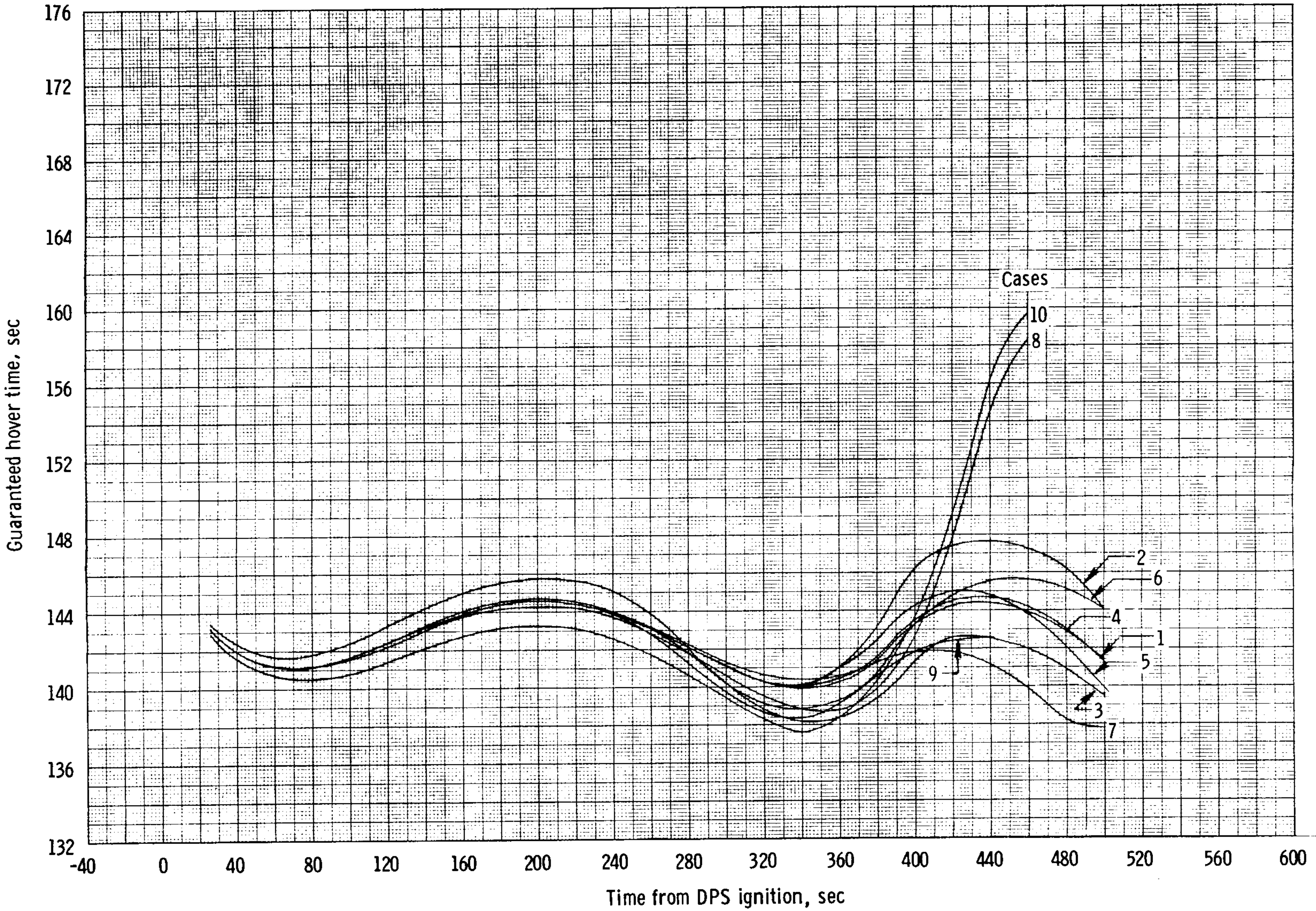

Figure 4. - Time history of guaranteed hover time based on the predicted fuel and oxidizer margins during the braking phase.

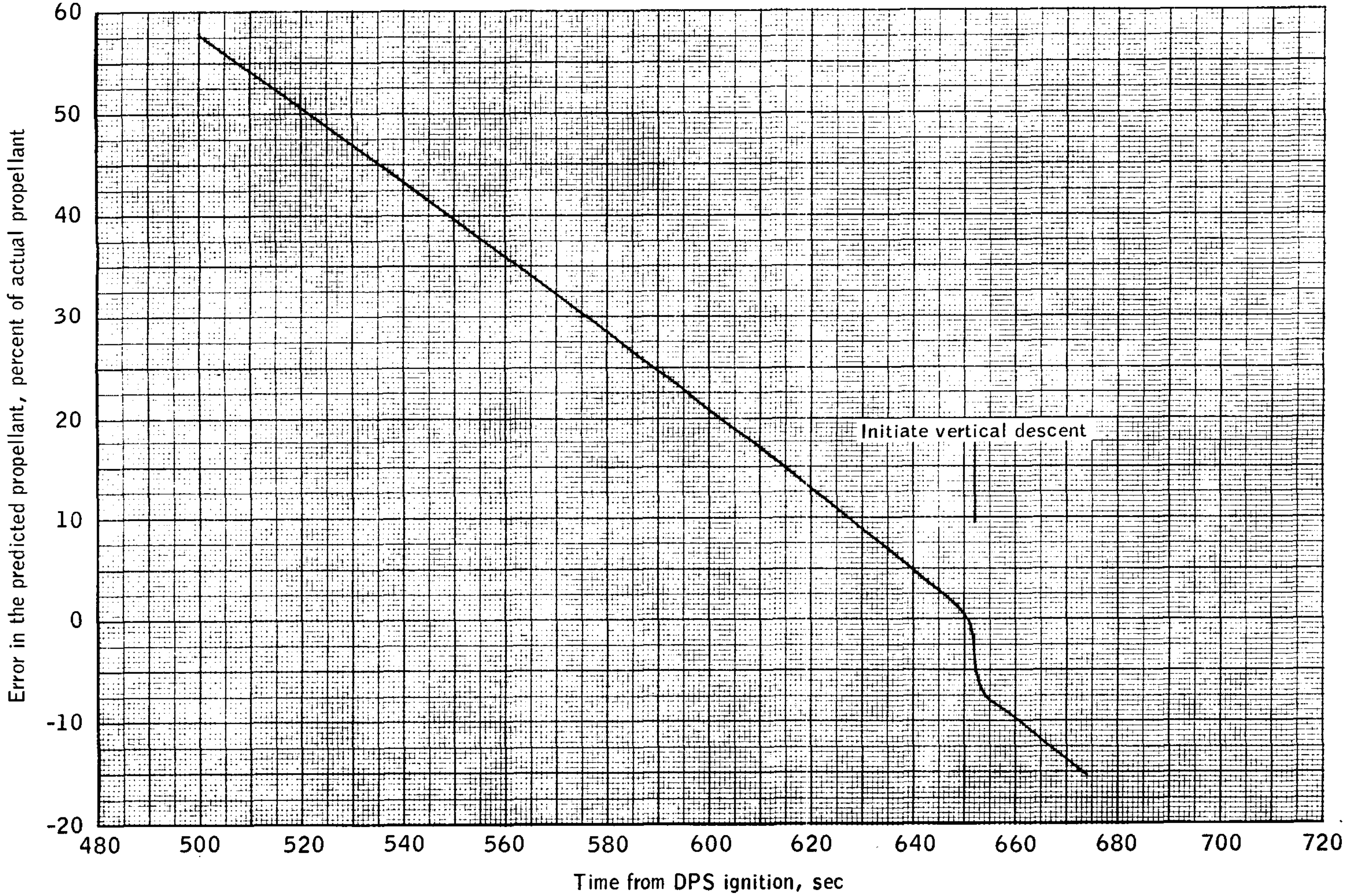

Figure 5.- Time history during the appraoch phase of the error in the predicted propellant margin computed without the lunar gravity affect.

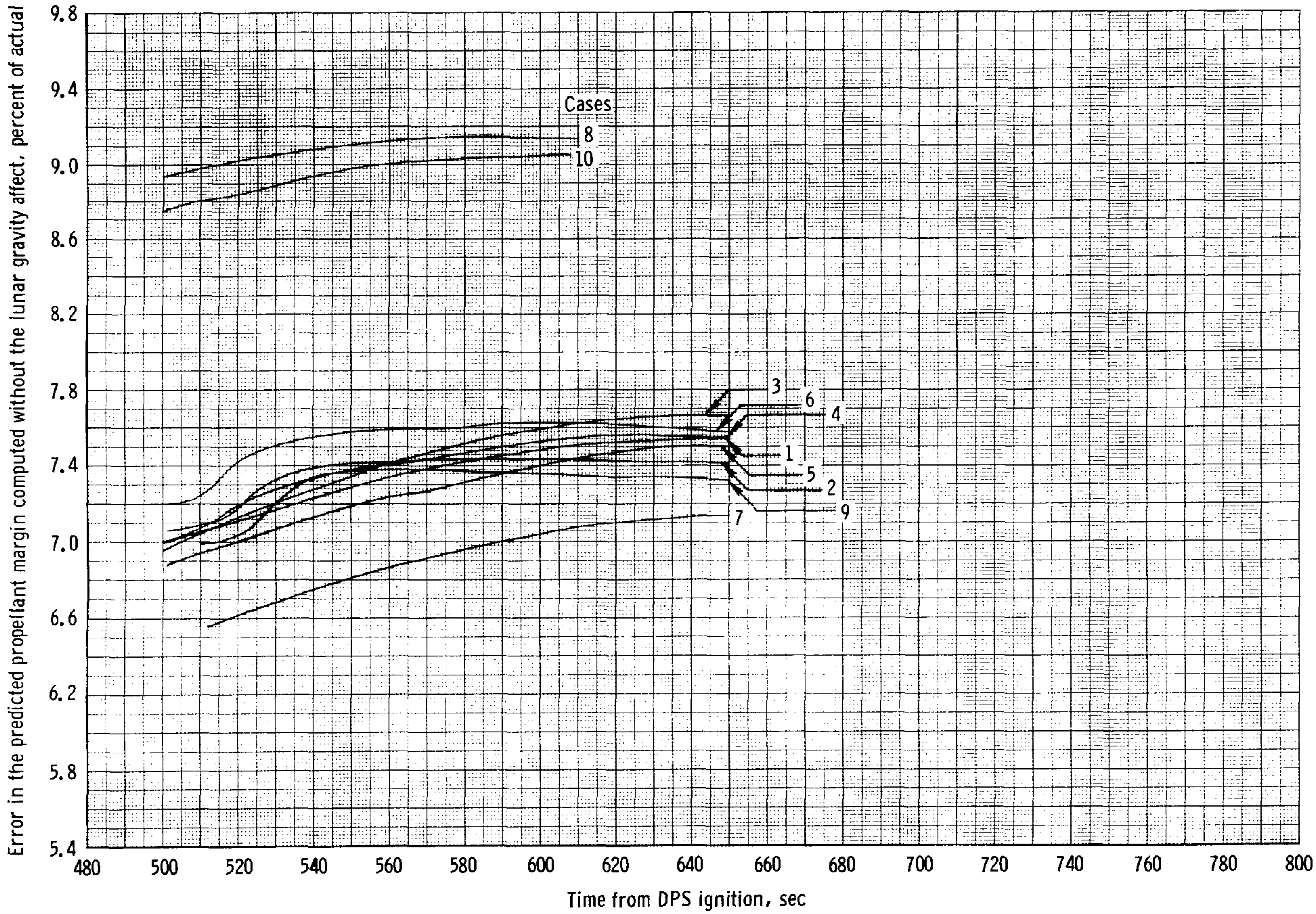

Figure 6.- Time history of the predicted propellant margin during the approach phase.

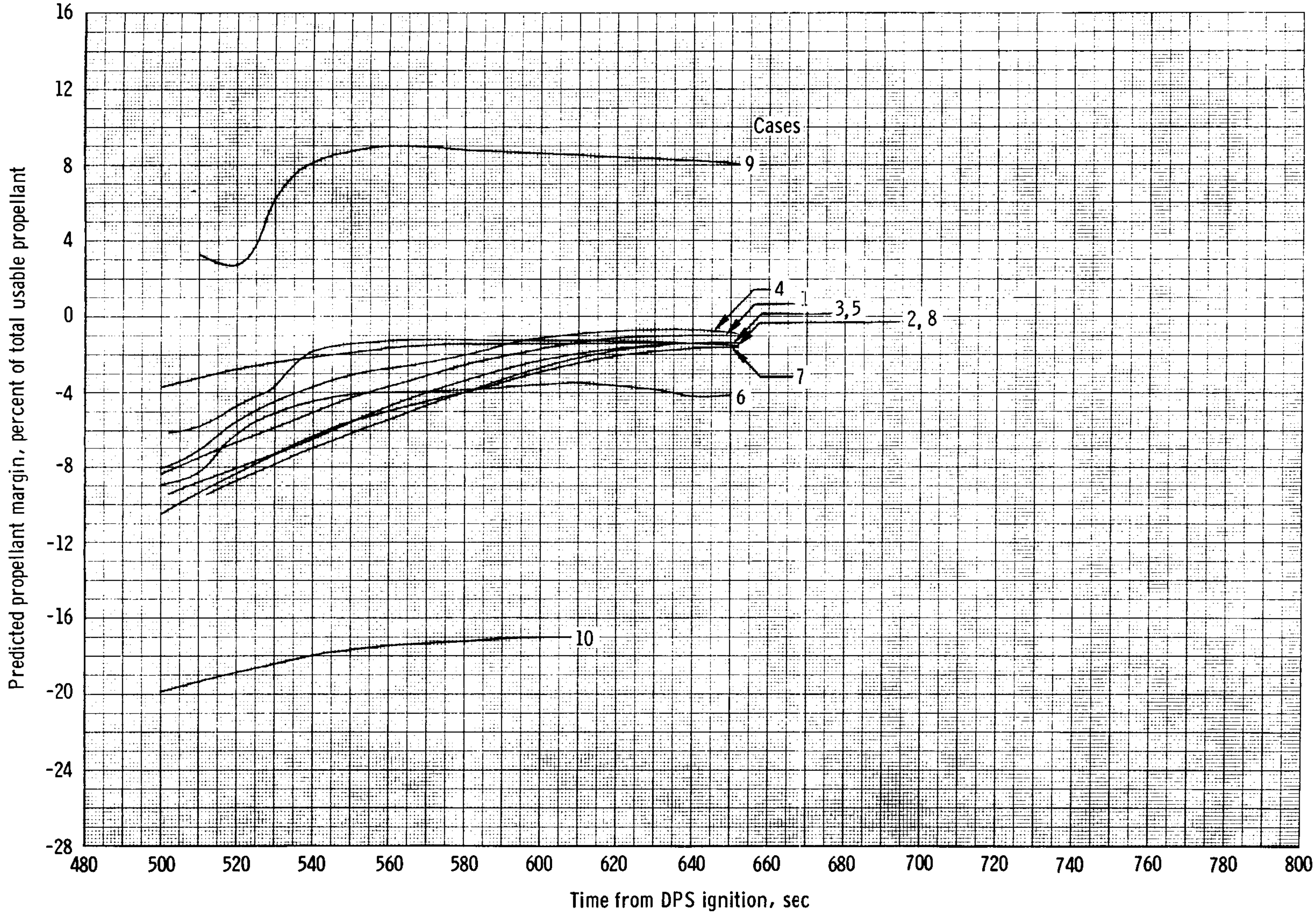

Figure 7. - Time history of the error in the predicted propellant margin during the approach phase.

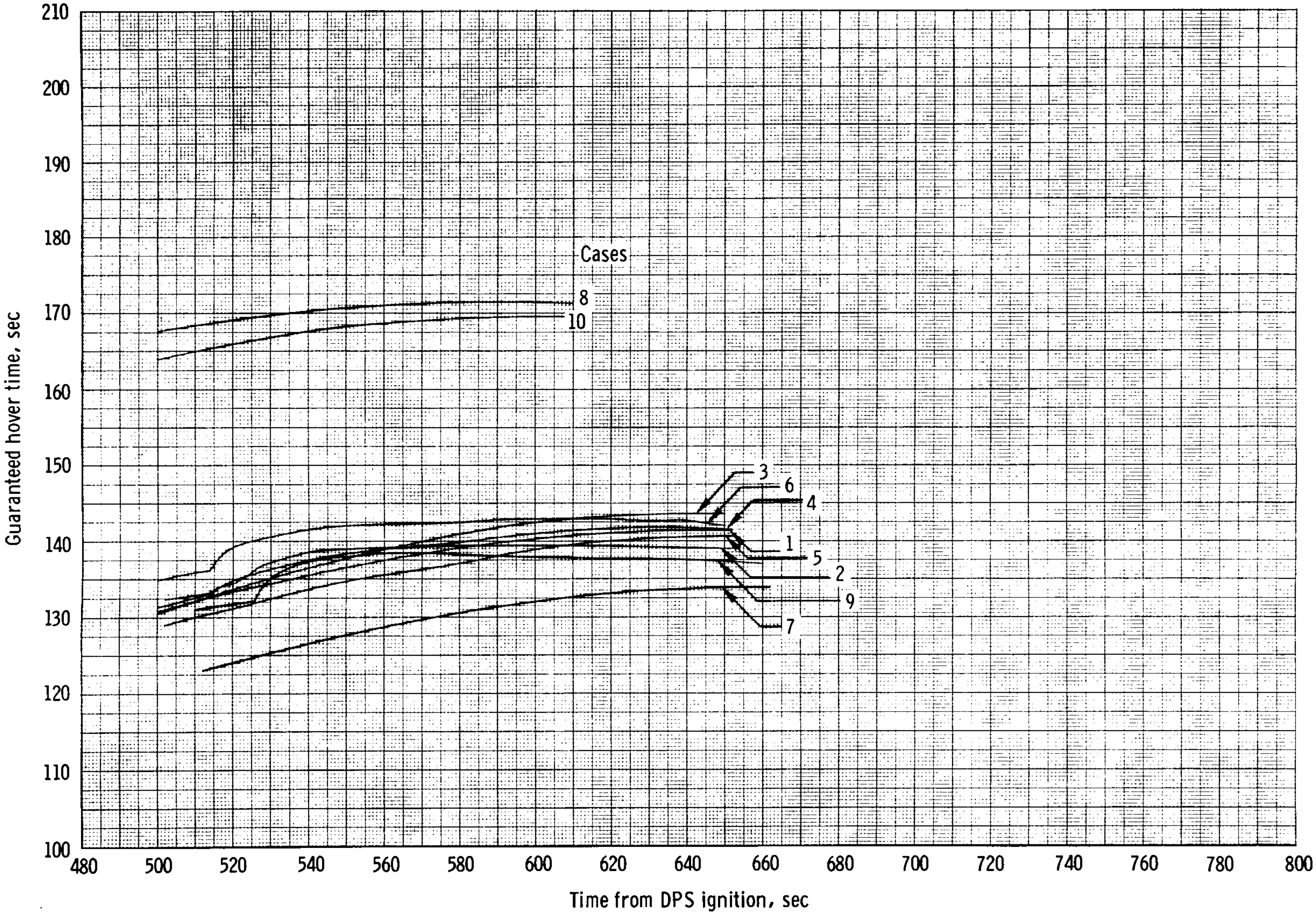

Figure 8. - Time history of guaranteed hover time based on the predicted propellant margin during the approach phase.

APPENDIX

LOGIC FOR COMPUTING MARGINS

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Braking Phase Display

$$\text{FU MAR} = \text{FU QTY} - \text{REQ PROP} \tag{A-1}$$

$$\text{OX MAR} = \text{OX QTY} - \text{REQ PROP} \tag{A-2}$$

where

FU MAR = instantaneous predicted fuel margin in percent of usable fuel

FU QTY = instantaneous actual usable fuel remaining in percent of total usable fuel (obtained from telemetry information)

OX MAR = instantaneous predicted oxidizer margin in percent of usable oxidizer

OX QTY = instantaneous actual usable oxidizer remaining in percent of total usable oxidizer (obtained from telemetry information)

REQ PROP = instantaneous propellant required in percent of total usable propellant nominally required for lunar landing (obtained from a curve fit which is a function of the navigated horizontal velocity)

Approach Phase Display

$$V_R = \left[1/3\ A_P + 2/3 \left(\left| \bar{A}_D + \bar{G}_M \right| \right) \right] * T_{GO} + 1/6\ J_D * T_{GO}^2 + \Delta V_{VD} \tag{A-3}$$

where

ΔV_R = estimated required ΔV from present position to lunar touchdown

A_P = present LM acceleration

$\bar{A}_D$ = desired acceleration at phase terminus (low gate)[a]

G_M = acceleration vector due to lunar gravity[a]

J_D = desired value of jerk (first time derivative of acceleration) at phase terminus (low gate)[a]

T_{GO} = estimated time-to-go until phase terminus

ΔV_{VD} = nominal value of ΔV consumed during the vertical descent phase[a]

The value of ΔV_R is then utilized to provide:

$$P_R = \frac{M_P + K_2}{K_1}\left(1 - e^{\frac{-\Delta V_R}{V_e}}\right)100 \qquad \text{(A-4)}$$

where

P_R = estimated required percent of usable propellant from present position to lunar touchdown

M_P = present estimated LM mass

K_1 = total usable propellant[a]

K_2 = known error in estimation of LM mass[a]

ΔV_R = estimated required ΔV from present position to lunar touchdown.

V_e = average exhaust velocity of DPS engine[a]

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[a]See table A-I for actual values used in simulations.

Propellant margin is then calculated as

$$PM = PCTQTY - P_R \tag{A-5}$$

where

PM = propellant margin

$PCTQTY$ = lesser of percent usable fuel or oxidizer from telemetry information

P_R = estimated required percent of usable propellant from present position to lunar touchdown

TABLE A-I.- PARAMETER VALUES USED IN ANALYTIC PROPELLANT MARGIN PREDICTION

Parameter	Value
$\bar{A}_D$, ft/sec^2	
X	0.05
Y	0
Z	-0.65
$\bar{G}_M$, ft/sec^2	
X	-5.3245
Y	0
Z	0
J_D, ft/sec^3	0.045636
ΔV_{VD}, fps	120
K_1, lb	17 510
K_2	0
V_e, fps	9 490

REFERENCES

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4. Kriegsman, B. A.; and Gustafson, D. E.: Simulation of Powered Landing Maneuver with Current Trajectory - Targeting Parameters, DPS Model, Terrain Model, and LR Dropout Boundaries. MIT/IL memorandum no. 20, June 14, 1968.